Open Access
Appl. Animal Sci. Bull., 2024, 1(1):11-22
ISSN (Online):3078-8862; ISSN (Print):3078-8854
DOI: https://doi.org/10.22194/AASB/24.1002
https://societyfia.org/journal/AASB

Organic Acids and Exogenous Enzymes in Poultry Nutrition: A Comprehensive Review

Ali Awais[1,*], Waqar Iqbal[1] and Abid Rasool[2]

[1]State Key Laboratory of Livestock and Poultry Nutrition and Feeding, Institute of Animal Sciences, Chinese Academy of Agricultural Sciences, Beijing 100193, China;[2]Department of Animal Nutrition, Faculty of Animal Production and Technology, University of Veterinary and Animal Sciences, 54000, Lahore, Pakistan
*Corresponding author's e-mail: drawais489@gmail.com; 2023Y90100037@caas.cn

Globally, the poultry sector plays a significant role in addressing food security and sustainability by providing a useful source of protein for billions of people. In modern chicken farming, proper nutrition is critical to maintaining optimum health, growth, and output. Proper feeding regimens that provide the birds with the nutrients they require based on their type, age, and stage of development are critical to improving efficiency and sustainability. The review concluded that using organic acids and exogenous enzymes as feed additives improves nutrient utilization and efficiency. Organic acids, such as formic and propionic acids, are useful in inhibiting pathogenic bacteria such as Salmonella and Escherichia coli in the stomach by maintaining an acidic environment. This acidic environment also promotes the existence of older, healthier gut bacteria, which aids in the absorption and digestion of food. As a result, the birds' gut condition improves, and they have fewer intestinal ailments, resulting in higher performance. Exogenous enzymes exist in non-starch polysaccharides (NSP) such as phytate, xylan, and β-mannan. They improve nutrient energy intake in animal bodies by changing the structures of non-carbohydrate parts of the feed. Furthermore, phytase reduces the need for inorganic phosphorus supplementation in feeds by hydrolyzing phytates that bind phosphorus. Furthermore, xylanase and mannase enzymes improve energy assimilation, reducing food waste as these two plant cell wall-wasting components are digested. Moreover, the use of these feed additives in chicken production contributes to the aims of sustainable agriculture by improving resource utilization and reducing the environmental effect of poultry farming. Innovation in feed techniques, such as using organic acids and exogenous enzymes, will help the global poultry business survive.

Keywords: Poultry nutrition, organic acids, exogenous enzymes, non-starch polysaccharides (NSP), antibiotic reduction, sustainability.

INTRODUCTION

In modern poultry farming, excellent nutrition is essential for health, growth, and productivity. To ensure birds get enough proteins, carbs, fats, vitamins, and minerals, poultry nutrition entails carefully regulating feed. Balance is crucial for bird growth and development, maximizing feed efficiency, lowering production costs, and enhancing flock health. (NRC, 1994). The nutritional requirements of poultry can vary based on their age, species, and production stage. For example, broiler chickens, bred for meat production, require diets promoting rapid growth and muscle development. However, layer hens need diets that boost egg output and quality (Leeson *et al*., 2005). Modern poultry diets contain several feed components and exact nutritional levels to suit these needs. Due to feed ingredient nutritional diversity, nutrient availability, and anti-nutritional variables that inhibit nutrient absorption, adequate nutrition is difficult. Modern poultry nutrition solutions include feed additives like organic acids and exogenous digestive enzymes to address these difficulties and improve feed efficiency. Natural organic acids can increase intestinal health and feed effectiveness in poultry feed. Lowering gastric pH is their main effect. This acidic environment promotes helpful bacteria and inhibits harmful germs like Salmonella and Campylobacter (Shang *et al*., 2018). Organic acids improve food absorption and digestion by suppressing pathogenic microbes in the gut microbiome. Formic and propionic acids are common organic acids in poultry diets. Formic acid has high antibacterial capabilities and reduces gut pathogenic microorganisms, reducing

Awais, A. and W. Iqbal. 2024. Organic Acids and Exogenous Enzymes in Poultry Nutrition: A Comprehensive Review. Applied Animal Science Bulletin 1: 11-22.
[Received 13 Mar 2024; Accepted 10 May 2024; Published 5 Jun 2024]
Attribution 4.0 International (CC BY 4.0)

gastrointestinal disease risk (Ricke *et al*., 2020). Propionic acid improves nutrient digestibility and feed conversion ratios in broilers, improving growth performance (Izat,1990). Organic acids work differently based on type, concentration, and poultry demands. To optimize their benefits, proper selection and use are needed. Organic acids are often combined with other feed additives for synergistic effects and feed quality. Another important feed ingredient for poultry nutrition is exogenous enzymes. Complex feed components that fowl are unable to digest on their own digestibility of nutrients are broken down by these enzymes (Bedford and Schulze, 1998). In poultry feed, exogenous enzymes improve nutrient digestibility and feed efficiency. A popular exogenous enzyme in poultry nutrition is phytase. Phytase breaks down phytic acid, a phosphate in plant-based feed that chickens cannot use. Phytase releases phosphorus from phytic acid, which helps bone formation and development. Farmers can eliminate supplemental inorganic phosphorus in the diet for cost and environmental reasons. Cellulase and xylanase are other exogenous enzymes that target plant-based feed fibers. Cellulase and xylanase breakdown cellulose and xylans, two fiber types (Knudsen, 1997). Breaking down these fibrous components promotes carbohydrate digestion and bird energy. Cellulase and xylanase improve growth and feed conversion ratios (Cowieson *et al*., 2013). Organic acids and exogenous digestive enzymes in poultry feed can boost performance. Organic acids improve digestive enzyme activity by generating a better environment. Conversely, exogenous enzymes may increase nutrient availability and lower the demand for organic acids for gut health. Including these feed additives in modern chicken farming shows an increasing understanding of feed formulation optimization and poultry health and productivity. Farmers can improve feed efficiency, nutrient utilization, and disease control by adding organic acids and exogenous enzymes to poultry diets.

***Organic Acids*:** Organic acid encompasses a wide range of compounds involved in fundamental metabolic processes within the body. These acids are typically water-soluble and acidic and do not react with ninhydrin, as they lack primary or secondary amines. Generally, organic acids include all carboxylic acids, whether or not they have keto, hydroxyl, or other non-amino functional groups, though most amino acids are excluded. Certain nitrogen-containing compounds, such as pyroglutamate, and amino conjugates like hippurate (benzoylglycine), are included, as are short-chain fatty acids.

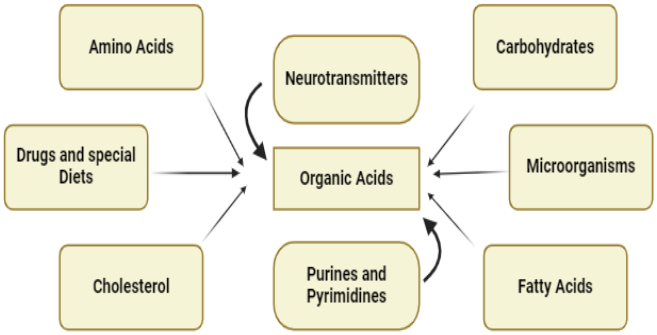

Figure 1. Pathways of organic acid production.

These can be classified as "simple monocarboxylic acids" like butyric, propionic, acetic, and formic acids, or as "carboxylic acids with hydroxyl group" like tartaric, citric, lactic, and malic acids, or as "short chain carboxylic acids containing double bonds like fumaric and sorbic acids. Any organic carboxylic acid with the general formula R-COOH, including fatty acids and amino acids, is categorized as an organic acid. Not every one of these acids affects the microbiota in the gut. Short-chain acids (C1–C7), which are naturally occurring and commonly found in plant and animal tissues, are organic acids that possess distinct antibacterial properties. They are also created when carbohydrates are fermented by microorganisms, primarily in the large intestine. In their sodium, potassium, or calcium salt forms, they can occasionally be detected. The pH range of 3 to 5 is known as the half-dissociation point (pKa) for the majority of organic acids that exhibit antibacterial action (Hajati, 2018). A list of organic acids used in the poultry industry is given below in Table 1.

Table 1. List of organic acids.

Organic Acid	Men (MJ/kg)
Acetic Acid	12.19
Propionic	17.78
Formic Acid	11.34
Butyric	22.43
Malic	9.79
Lactic	14.53
Citric	10.29

Sources: (Hajati, 2018)

***Mechanism*:** There are numerous advantages that organic acids provide for the growth and health of the digestive system. Nevertheless, our understanding of their exact underlying mechanisms of action is still lacking. These mechanisms can be partially explained by a number of factors, including:

(1) Mineral chelation and intermediate metabolism.
(2) Pathogenic bacteria-preventing ability.

(3) They lower stomach pH and increase pepsin production to improve digestion.
(4) Their ability to inhibit stomach emptying and sustain enzyme secretion.

Biological systems Buffering organic acids regulate pH. They can give or take up protons to maintain pH, which is necessary for enzyme activity, cell function, and many biological processes. Lipophilic weak acids' antimicrobial effects may affect membrane function, preventing substrate molecules like phosphate, amino acids, and organic acids from entering cells (Freese *et al*., 1973). Previous investigations (Booth and Stratford 2003;Cherrington *et al*., 1991) have addressed additional pathways that could restrict microbial development by OA. These lipid-soluble weak acids are thought to work primarily by directly lowering the extracellular pH through the release of hydrogen ions (protons) into the surrounding medium through their ion dissociation. All agree, however, that once they cross microbe cell membranes, their main mechanism of action is to reduce the cytoplasmic pH. Figure 2 explains how organic acids work.

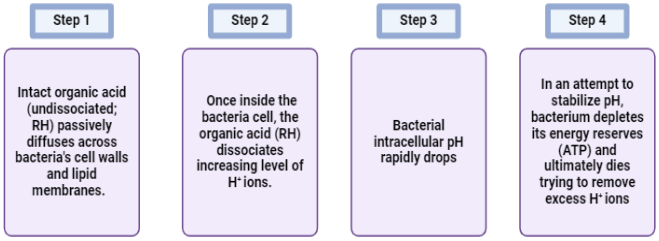
Step 1
Intact organic acid (undissociated; RH) passively diffuses across bacteria's cell walls and lipid membranes.
Step 2
Once inside the bacteria cell, the organic acid (RH) dissociates increasing level of H+ ions.
Step 3
Bacterial intracellular pH rapidly drops
Step 4
In an attempt to stabilize pH, bacterium depletes its energy reserves (ATP) and ultimately dies trying to remove excess H+ ions

Figure 2. Mode of Action how do organic acids work.

In poultry operations, acidifiers are used in three primary ways (Hajati, 2018):

1. ***In feed*:** Organic acids, added in solid form to poultry feed, help prevent mold growth and lower the pH in the birds' crops.
2. ***In litter*:** Sprayed onto poultry litter, they target bacteria that break down uric acid, reducing ammonia emissions.
3. ***In water*:** Injected into drinking water, organic acids eliminate bacteria, enhance the effectiveness of chlorine, and lower the pH in the birds' feed.

***Exogenous Enzymes*:** The use of enzymes in animal feed is critically important, particularly in developing countries where the rising cost of feed ingredients poses a significant challenge. As a result, more affordable and unconventional feed ingredients, which tend to contain higher levels of Non-Starch Polysaccharides (NSPs) alongside starch, must be used. NSPs are polymeric carbohydrates that differ from starch in both composition and structure (Morgan *et al*., 1995) and are chemically cross-linked, making them difficult for poultry to digest (Adams and Pough, 1993; Annison, 1993). Certain NSPs exhibit water solubility and are known for creating a gel-like, viscous consistency in the intestinal tract, thereby diminishing gut efficiency. Water-soluble arabinoxylans, classified within the pentosan group, are regarded as the primary contributing factor. Pentosans enhance water absorption in poultry, resulting in moist, adhesive faeces that generate significant litter problems, thereby undermining hygiene and carcass quality (Dunn, 1996). Additionally, ß-glucans negatively affect nutrient absorption, especially proteins and starch, contributing to high viscosity in the chicks' small intestines (Hasselman and Aman, 1986). Since poultry lacks the enzymes necessary to hydrolyze the NSPs found in grain cell walls, these carbohydrates remain undigested, resulting in reduced feed efficiency. However, research indicates that the adverse effects of NSPs can be mitigated by incorporating exogenous enzyme preparations into poultry diets (Creswell, 1994). These enzymes break down NSPs, reduce intestinal viscosity, and ultimately improve nutrient digestibility by enhancing gut performance.

TYPES

***Carbohydrases*:** Carbohydrases reduce polymeric carbohydrates' molecular weight. Dietary carbs affect gut microbiota, absorption, and immunological response in non-ruminants (Bach Knudsen *et al*., 2017). Cereal fibers contain NSP components like cellulose, β glucans, arabinoxylans, and resistant starch (RS), which may impact overall health. The molecular weight of polymeric carbohydrates is reduced by carbohydrases. Dietary carbs affect gut microbiota, absorption, and immunological response in non-ruminants (Duarte *et al*., 2021).

***Xylanase*:** Xylanases belong to six glycoside hydrolase families that target unique substrates (Tiwari *et al*., 2020). Bacteria, fungi, and yeast produce these enzymes, with most commercial xylanases coming from bacteria or filamentous fungi (Bhardwaj *et al*., 2019). Arabinoxylans, made of arabinose and xylose, are the main non-cellulosic polysaccharide in corn-soybean meal-DDGS diets and cereals. Xylanase enzymes function by cleaving the β-1,4-glycosidic linkages in the AXE backbone, resulting in the formation of smaller molecules such as xylo-oligosaccharides or arabinoxylo-oligosaccharides. While improvements in poultry performance through exogenous xylanase are often linked to reduced gut viscosity and better nutrient absorption, xylanase also offers other benefits. It can enhance gut health by improving intestinal structure, fortifying the intestinal barrier, modulating immune responses, and reducing oxidative stress both locally and systemically (Valente Junior *et al*., 2024).

***β-Mannanase*:** β-Mannanases are endohydrolase enzymes that break the 1,4-β-d-mannan bonds within glucomannans and galactomannans (Mccleary *et al*., 1987). Mannan is the second most prevalent hemicellulosic polysaccharide in cereals and their by-products, after arabinoxylans (AX) Dhawan and Kaur (2007). In non-ruminant animals, digestive enzymes in the upper gastrointestinal tract do not easily break down β-mannans, like other dietary NSPs. In pigs and poultry,

soluble β-mannans can increase intestinal viscosity, affecting nutritional absorption, particularly glucose and lipids (Balasubramanian *et al*., 2018; Lee *et al*., 2003). Research has shown that β-mannanase enzymes degrade the β-mannan backbone, producing short-chain β-1,4-mannoligo-saccharides (β-1-4-MOS). These studies show that β-1-4-MOS can boost lactic acid production and suppress harmful bacteria like Escherichia coli and *Salmonella* spp. in both monoculture and co-culture fermentation environments. β-mannan hydrolysis products can act as selective substrates for beneficial gut bacteria such as *Bifidobacteria* (Kiarie *et al*., 2022).

***β-Glucanase*:** Many studies have focused on different aspects of dietary fiber, particularly arabinoxylans. β-glucan, a key cell wall component, is more concentrated in barley and oats, then in rye and wheat. While there has been extensive research on β-glucans in pigs, due to their use as models for human health studies, poultry studies have been comparatively limited. β-Glucans are polymers composed of D-glucose units connected by β(1→3), β(1→6), or β(1→4) linkages, and are found in a variety of feed sources such as cereals, yeast, and mushrooms. In cereals such as oats and barley, β-glucans are primarily linear chains of glucose connected by β(1→3) and β(1→4) bonds, featuring two or three β-(1-4) linkages interrupted by a single β-(1-3) bond. β-glucans can vary in amount and structure within the same grain due to genetic and environmental factors. β-glucanase is often used to mitigate the negative impacts of β-glucan in barley and oats, with significant research dedicated to the combined use of β-glucanase and xylanase in animal diets. Xylanase boosts β-glucanase activity in grains, enhancing the nutritional value of barley and oats. Research indicates that adding β-glucanase and xylanase to poultry diets improves weight gain, feed efficiency, energy, dry matter, and crude protein digestion by reducing digesta viscosity and promoting non-starch polysaccharide breakdown (Clarke *et al*., 2018; Duarte *et al*., 2021; Tsai *et al*., 2017; Munyaka *et al*., 2016).

***α-Amylase*:** Corn is chicken diets' main carbohydrate source, providing energy for growth and development. Amylose and amylopectin, two complex carbohydrate components, are unique in structure. Amylose consists of straight α(1-4)-linked anhydroglucose chains, while amylopectin has a branching structure with α(1-6)-linkages (Kumar and Chakravarty, 2018; Cowieson *et al*., 2019). Endogenous amylase in animal intestines breaks down starch, unlike non-starch polysaccharides. However, post-weaning piglets and early chicks produce little endogenous amylase, thus exogenous amylase must be added to their meals to increase starch digestion. Since 40% to 60% of the meal during the finishing phase contains starch, natural amylase production may not be enough, stressing the necessity for exogenous amylase supplementation in animal diets (Giuberti, 2014).

***Phytase*:** Phosphorus is an important mineral that contributes to energy metabolism, nucleic acid synthesis, and the structure of cell membranes. Its primary function, though, is in bone formation and mineralization, where it also serves as a reserve that can be mobilized for various metabolic functions (Saraiva, 2009). Although phosphorus is essential, the form found in plant-based feed, known as phytic phosphorus, has traditionally been considered inaccessible to non-ruminants. In many grain-based diets for pigs and poultry, phytic acid can make up to 80% of the total phosphorus. This compound can form complexes with other minerals in the gastrointestinal tract, reducing their availability. Additionally, it can bind to amino acids, proteins, and enzymes such as trypsin and α-amylase, which may hinder their function and disrupt protein and carbohydrate digestion Singh and Krikorian (1982). The ability of non-ruminants to utilize phytic phosphorus is restricted by their low endogenous phytase activity in the small intestine, which is insufficient for breaking down phytate and releasing phosphorus for absorption. As a result, diets frequently incorporate high levels of inorganic phosphorus to meet nutritional requirements. To improve the bioavailability of phosphorus from phytic sources, several nutritional strategies have been investigated Lei and Porres (2003).

***Enzyme's mode of action*:** Adding enzymes to feed enhances nutrient utilization and overall performance in birds through several mechanisms:

***Reducing gut viscosity*:** Cereals typically contain a significant amount of their energy as non-starch polysaccharides (NSPs), which include soluble, indigestible polysaccharides like arabinoxylans (found in wheat), mixed-link β-glucans (in barley and rye), lignin, and limit dextrin, as well as anti-nutritional components such as phytic acid and cellulose fiber. These NSPs can absorb considerable amounts of water, increasing gut viscosity. This increased viscosity can slow the passage of digesta, disrupt the mixing of bile, pancreatic, and intestinal secretions, and negatively impact nutrient absorption. Additionally, it may result in stickier feces. The use of appropriate multi-enzyme preparations helps improve animal performance by:

- ***Enhancing endogenous enzyme effectiveness*:** Enzymes break down the gel-like structures of soluble fibers, allowing the bird's digestive enzymes to function more efficiently. This process leads to improved digestibility of starch, protein, fat, amino acids, and energy.
- ***Modifying feed passage rate*:** By reducing the water-holding capacity of gut contents, enzymes increase the dry matter content of the feed, which can stimulate feed intake.
- ***Improving excreta characteristics*:** Enzyme supplementation can decrease the moisture content of excreta, affecting both the volume and composition of droppings. Better protein digestion generally results in lower excreta output.

- ***Addressing litter problems*:** Reduced viscosity enhances nutrient digestion, reduces water intake, and helps mitigate litter issues.

***Release of nutrients*:** Enzymatic depolymerization of NSPs in the gut releases previously bound nutrients. This process frees up starches that were masked by cell structures, increasing the availability of metabolizable energy. Proteases also release proteins, leading to improved mineral absorption and overall nutrient utilization.

***Availability of phosphorus*:** Cereals and oilseeds have a phytate content of 1-2%, which constitutes 60-90% of the total phosphorus in seeds. Phytase enzymes break down phytic acid into myo-inositol and phosphoric acid through a series of steps, generating myo-inositol phosphate intermediates (IP5, IP4, IP3, IP2, IP1) that enhance the absorption of phosphorus.

***Increasing available energy*:** Adding enzymes to poultry diets, particularly those based on wheat and barley, increases the available energy content. This enhancement is attributed to improved digestibility of carbohydrates, which boosts overall energy utilization (Van der Klis *et al*., 1995; Partridge and Wyatt, 1995).

***Enhancement of nutrient digestibility*:** Research has shown that enzymes can enhance both performance and nutrient digestibility in poultry diets containing cereals such as barley, maize, oats, rye, and wheat, as well as legumes like lupines. The extent to which enzyme supplementation affects dry matter digestibility varies based on the diet and the animal species, with poultry experiencing increases ranging from 0.9% to 17%. In monogastric diets, glycanases are commonly used enzymes. These enzymes degrade non-starch polysaccharides (NSPs) into smaller fragments, reducing their viscosity and thereby enhancing the digestibility of nutrients (Dida, 2016). Figure 3 explains the whole mechanism of enzymes.

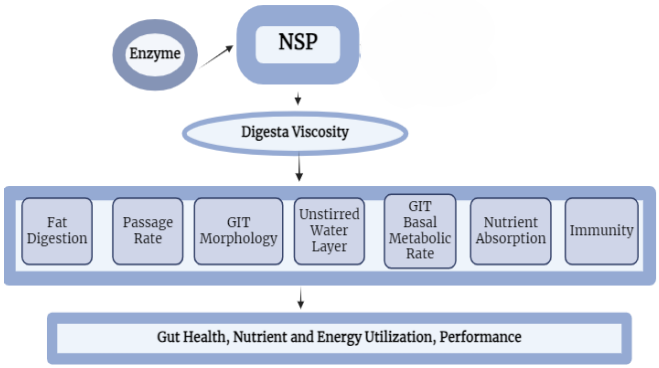

Figure 3. Flowchart the mode of action of enzyme supplementation.

***Using organic acid and exogenous enzyme*:** The primary issue facing the poultry industry is its reliance on outside sources for parent stock, feed additives, medications, vaccines, and raw materials (particularly corn and soybeans). This dependency hurts the industry's ability to compete in international markets due to rising production costs. With the use of antibiotic growth promoters prohibited, farmers are forced to look for and employ other promoters in order to achieve the best possible performance from their broilers. Therefore, their usage in productive livestock feed diets causes the building of resistance against human pathogenic microorganisms, Thus, to boost productive performance and prevent the occurrence of certain diseases in poultry, several chemicals have been studied in recent years as potential alternatives to growth-promoting antibiotics. Organic acids (OA), prebiotics, probiotics, enzymes, and mixtures of these goods are examples of these alternative feed additives. Exogenous enzymes are added to broiler meals to improve food digestion, reduce antinutritional effects, and raise productivity indices. Protein digestibility has been improved and gut microbiota regulation has been achieved with the application of organic acids. Live weight, body weight increase, and feed conversion rate all improved more in broiler chicks fed dietary organic acids (Abdel-Fatt *et al*., 2008; AM, 2017). Organic acid improves protein and energy digestibility by reducing microbial competition with the host for nutrients and also reduces ammonia emission, which ultimately adds benefits to the broiler. Therefore, feeding organic acid with enzymes has received more attention from animal nutritionists (Dibner and Buttin, 2002). For chickens to grow, phosphorus is necessary, especially for the development of their bones. Animals that are monogastric eat mostly oilseeds and cereal grains, which are high in P and contain either phytic acid or phytate. Because the digestive tract of chicken has low levels of phytase activity, the P in this form is typically not available to them (Nelson, 1976; Cromwell, 1992). Research on the impact of microbial phytase in monogastric animals' digestive tracts showed that lower pH levels could maximize the enzyme's activity. Accordingly, some writers (Brenes *et al*., 2003) assessed the possible advantages of citric acid on the effectiveness of microbial phytase preparations in pigs and grilled chickens. The effectiveness of organic acids in enhancing pig and chicken development performance has been assessed multiple times (Jonbloed *et al*., 2000). Nevertheless, aside from citric acid, not much research has been done on the effectiveness of organic acids in enhancing phytate P utilization.

***Impacts of Organic Acids in Poultry Nutrition*:** Bird immunity depends on dietary OA. Minimizing subclinical infections and encouraging beneficial bacteria growth may improve nutrition digestibility and reduce gut-associated immunological tissue and microorganism nutrient requirements (Dibner and Buttin 2002; Humphrey and Lanning 1988). OA enhances feed conversion, average live weight, daily gain (BWG), and feed consumption. Dietary organic acids reduce harmful microorganisms, improving poultry performance. Supplementing diets with organic acids

can control Salmonella, Campylobacter, and Escherichia coli, the most frequent intestinal bacteria in poultry (Van Immerseel *et al*., 2006; Al-Kassi and Mohssen 2009). Poultry products often contain *salmonella*. This biological threat must be controlled for public health. By introducing organic acids to feed or water at the right periods, chicken carcass and egg contamination can be reduced (Russell and Diez Gonzalez, 1998). Good gut health is crucial for poultry development and feed efficiency. Supplementing broiler chicks with organic acid (1.0% sorbic acid and 0.2% citric acid) significantly enhanced villus breadth, height, and area in the duodenum, jejunum, and ileum at 14 days of age (Kum *et al*., 2010; Rodríguez-Lecompte *et al*., 2012). Butyrate increased duodenal villus length and crypt depth in broilers at 0.2%, 0.4%, or 0.6% (Leeson *et al*., 2005 ; Panda *et al*., 2009). Young birds may benefit from butyrate supplementation for gut development. Dietary OA dramatically lowered cholesterol, total lipid, and low-density lipoprotein with increased calcium, phosphorus, and magnesium (Kamal and Ragaa 2014). Similarly, (Ma *et al*., 2021) reported that broilers' productivity, average daily growth, and FCR improved with 3000 mg/kg mixed organic acid supplementation. OA supplementation increased breast milk saturated, unsaturated, and polyunsaturated fatty acid ratios. Recently, (Ebeid *et al*., 2021) observed Broiler chicken fed organic acid (0.03% and 0.06%) and probiotics (0.02%) showed significant improvements in growth, antioxidant defense, and humoral and cell-mediated immunological response. Overall, the foregoing research showed that OA can replace ABGP in broiler diets to improve performance,

Table 2. Organic acids impact on poultry health.

Organic Acids	Animal Model	Function	Dosage	Benefits	Mode of Action	References
Butyric acid	Broiler Chicken	Alternative to growth promoter	2 kg/ton mono-,di-, and triglycerides of butyric acid	↑Intestinal health and performance in broiler chickens ↑Productivity index, feed conversion rate, and growth rate	↑Antimicrobial effects against pathogen ↑Villus height and crypt depth ↑Nutrient digestibility	Ficagna *et al.* (2002)
Citric acid and acetic acid	Broiler Chicken	Pharmaceutical agents	1:1 of acetic acid and citric acid	↑FCR and weight gain ↓Liver weight ↑Heart and gizzard weight	↑Digestion and absorption of nutrients ↑The secretion of thyroid hormone	Abdelrazek*et al*. (2016)
Humic acid and organic acid	Broiler Chicken	Immune Booster	.02%OA and 0.1%HA + 0.02% OA	↑Color and smell of meat ↓Hepatic lesions ↑White pulp of spleen ↓Heterophil to lymphocyte (H/L) ratio	↑Immune functions ↑Nutrient digestibility ↑preservation of histological structure in the spleen and liver	Akaichi *et al.* (2022)a
Fumaric acid	Japanese quail chicks	Health promotiong agent	5, 10, 15, and 20gFUA/kg diet	↑Growth performance ↑Digestibility of crude protein and metabolizable energy ↓Total protein, globulin concentrations and high-density lipoprotein in blood	↑Amylase enzyme activity ↑nutrient digestion and absorption ↑Immunoglobulins (IgG andIgM) ↓Proliferation of pathogenic bacteria	Reda *et al.* (2021)
Malic acid	Broiler Chicken	Antioxidant and Acidifying agent	4, 8, and 12 g/kg	↑Feed intake and daily weight gain of the broilers andwater-holding capacity ↓The feed conversion ratio, dripping loss and cooking loss of meat Feed preservation	↓superoxide dismutase and the levels of immunoglobulin A and glutathione in serum ↑mmunoglobulin G and M andalso alter the microbial diversity of intestinal bacteria	Qiu *et al.* (2022)
Ascorbic acid and Probiotic	Broiler Chicken	Antioxidant and Immune Enhancer	200 mg/kg ascorbic acid and1 g/kg of probiotic	↑Antioxidant Defence ↑Immune function ↑Antioxidant capacity ↓Heat stress and oxidative stress	↓8-OHdG gene (which isa biomarker for oxidative DNAdamage) ↓HSP70 (which is a heat shockprotein) ↑IL-10 (which is an anti-inflammatory cytokine)	Sumanu *et al.* (2023)

Table 3. Exogenous Enzymes impact on poultry health.

Enzymes	Classification	Production organism	Functions
α-Amylase	Carbohydrase	*Aspergillus* spp., *Bacillus* spp., *Rhizopus* spp.	Hydrolsis of starch
Cellulase	Carbohydrase	*Aspergillus niger*, *Saccharomyces* spp.	cellulose breaks down
β-Amylase	Carbohydrase	*Barley malt*	Starch hydrolysis produces maltose
Phytase	Phosphatase	*Aspergillus* spp., *Penicillium* spp., *Phytase canola*, *Pichia pastoris*, *Aspergillus niger*, *Escherichia coli*	Hydrolyzes phytate
Pectinase	Carbohydrase	*Aspergillus aculeatus*, *Aspergillus niger*, *Rhizopus oryzae*	Breaks down pectin
Xylanase	Carbohydrase	*Aspergillus* spp., *Bacillus* spp., *Humicola* spp., *Penicillum* spp., *Trichoderma* spp.	Hydrolyzes xylans
β-Glucanase	Carbohydrase	*Aspergillus* spp., *Bacillus* spp.	Hydrolyzes xylans

Sources: (Khusheeba and Sajid, 2013)

health, and immune response. More details can be seen in Table 2.

***Impacts of Exogenous Enzymes in Poultry Nutrition*:**Poultry and swine feeds often contain enzymes to promote nutrient utilization and meat output. Today, most poultry and swine diets contain pentosanases and small grains, including wheat, barley, and oats. Besides improving nutritional digestibility, enzymes improve the gut microbial environment (Fischer and Classen, 2000). Pigs, poultry, and other monogastric animals lack rumen microflora alloenzymes, therefore they need enzymes in their meals to maximise nutrient utilisation from complex feed components. Digesting animal feed using enzymes increases nutrient availability (Khusheeba and Sajid, 2013). Enzymes that degrade non-starch polysaccharides (NSP) in broiler diets made from 'viscous' cereals like wheat and barley (Bedford and Schulze, 1998). Non-starch polysaccharides mostly present in raw materials used for poultry diets are pectins, cellulose, mixed-linked β-glucans, and arabinoxylans (Parsippany, 2008). To depolymerise these NSPs, enzymes specific to their main and side chains are needed. First, NSP-degrading enzymes were used in barley-based broiler diets. The application of NSP-degrading enzymes in barley and wheat-based broiler diets increased litter quality and performance. Thus, NSP-degrading enzymes in wheat and barley-based broiler feeds are widely used (Bedford, 2009). Glucanase and xylanase improved FCR and ileal nutrient digestibility in maize/soy diets (Cowieson *et al*., 2010). A synergistic impact occurred when both enzymes were added concurrently, yielding larger benefits than either alone but less than the sum of their effects. Further benefits of enzymes can be seen in Table 3.

***Environmental and Economic Impact*:** According to Williams (1995), environmental pollution is the result of poisons, compounds made by humans, animal welfare, and other organisms. Poultry husbandry is becoming a more environmentally friendly activity due to the effective capacity of phytase to improve the utilization of phytic phosphorus, mainly from feedstuffs with high phytate levels. This reduces the pollutant potential of excreta. (Schoulten *et al*., 2003). Even when animals are raised under optimal conditions, receiving high-quality nutrition and receiving the right care, significant losses still happen during the process of converting food into animal products. Following the demonstration of the effectiveness of Carbohydrases, these could encourage the production of more subproducts from vegetable sources, lowering the cost of diets and helping to protect the environment by lowering nutrient excretion (Schoulten *et al*., 2003). According to the animal's ability to use these nutrients, which is enhanced by the addition of exogenous enzymes, environmental pollution from fecal excretion of nitrogen and phosphorus can occur at a higher or lower. As omnivorous creatures, birds are incapable of breaking down non-starchy carbohydrates like those found in soluble and insoluble fiber. As a result, when given to birds instead of animals with higher capacities for fermentation, like swine, many vegetable ingredients commonly found in poultry diets have lower digestibility values. Enhancing the ability of birds to digest food by adding extra enzymes is suggested as a viable option to both increase animal performance and decrease the amount of excrement. This lowers the potential for contamination in the production environment and, as a result, becomes a viable option to lessen the effects of removing growth promoters (Vieira, 2003). In line with (Rutherfurd *et al*., 2002) The addition of microbial phytase to poultry diets has been shown to retain minerals and improve the digestibility of amino acids. This has the potential to lower expenses and mitigate environmental effects by reducing the concentration of nitrogen and phosphorus in excreta. Using OA in poultry production not only makes sense but also guarantees a lower ecological, environmental, and financial overhead when compared to alternative supplements that are already on the market. Improved nutrient digestibility, for instance, will have a nutrient-sparing effect, which will also cut losses and improve production performance, hence lowering the risk of environmental pollution from animal production (Lückstädt and Mellor, 2011). This is especially true for a decrease in

environmental problems linked to minerals and nitrogen from poultry facilities (Dibner and Buttin, 2002).

***Challenges*:** Poultry nutrition is negatively impacted by feed component costs, which account for 70% of production expenses (Thirumalaisamy *et al*., 2016). The unclear global commodities markets and severe rivalry for soy and maize affect chicken feed prices and duration (Mottet and Tempio, 2017). Nutritional imbalances including protein and nutritional deficiencies might influence poultry development and production. Plant-based diets with tannins and phytates make it more fierce for animals to absorb nutrients. Heat stress makes animals utilize less and utilize nutrients less effectively, hurting performance (Yahav, 2009). We need to find new, sustainable feed additives that animals struggle to digest, compounding these issues (Vahjen *et al*., 2014).

Challenge	Description	References
Feed Ingredient Availability and Cost	Poultry diets rely heavily on maize and soybean meal, leading to price fluctuations due to competition with human food markets and global disruptions like droughts and political instability. This is more severe in developing countries.	(Tacon *et al*., 2022).
Nutritional Imbalances and Feed Quality	Balancing the right amounts of energy, protein, and micronutrients in poultry feed is challenging, and over- or under-supplementation can impair growth and immune response.	(Kallam and Sejian, 2021),
Anti-Nutritional Factors	Plant-based ingredients like legumes contain anti-nutritional factors (e.g., tannins) that reduce digestibility and nutrient absorption, especially when alternative or low-cost feedstuffs are used.	Kallam and Sejian, 2021
Impact of Heat Stress	Heat stress, especially in tropical and subtropical regions, reduces feed intake, nutrient absorption, and overall productivity, compromising growth and feed efficiency.	(Lara and Rostagno, 2013).
Water Quality	Clean water is essential for feed digestion, and contaminated water introduces pathogens that impair nutrient absorption and cause gastrointestinal diseases.	
Alternative Protein Sources	Alternatives to expensive soybean meal, such as insect meals, algae, and single-cell proteins, have been explored, but digestibility, availability, and cost remain challenges.	(Huis *et al*., 2013).
By-products and Agro-Industrial Residues	Agro-industrial by-products like palm kernel meal and rice bran are explored as feed alternatives but often have variable nutrient content and toxins, requiring further processing.	
Consumer Preferences and Regulatory Constraints	Increasing demand for antibiotic-free diets has led to restrictions on AGPs, with alternatives like probiotics and prebiotics being explored, though their effectiveness varies across different environments.	(Dibner and Richards, 2005), (Gaggìa *et al*., 2010).
Mycotoxin Contamination	Mycotoxin contamination of feed ingredients is a persistent issue, especially in humid regions, leading to reduced feed intake and impaired bird health.	(Ochieng *et al*., 2021)

***Conclusion*:** Organic acids and exogenous enzymes in poultry feed are a major development in animal management, improving production and sustainability. Organic acids increase gut health, nutrient absorption, and pathogen management, whereas exogenous enzymes improve feed digestion, nutrient bioavailability, and environmental waste relief. These additives promote antibiotic-free, sustainable chicken production while meeting customer preferences and maintaining poultry enterprises' economic efficiency. The poultry business must continue research and innovation in these areas to satisfy global food production and environmental sustainability issues.

***Authors' contributions*:** AA led the conceptualization, conducted the literature search, and wrote most of the manuscript. WI and AR assisted with literature analysis, drafted the methodology, proofread and contributed to editing of this manuscript.

***Conflict of Interest*:** The authors affirm that there is no conflict of interest.

***Ethical statement*:** This review paper adheres to ethical guidelines and standards. All literature cited has been properly referenced, and no original research involving human or animal subjects was conducted.

***SDGs addressed*:** Zero Hunger, Good Health, and Well-Being.

REFERENCES

Al-Kassi, A.G. and M.A. Mohssen. 2009. Comparative study between single organic acid effect and synergistic organic acid effect on broiler performance. Pakistan Journal of nutrition 8:896-899.

Dibner, J. and P. Buttin. 2002. Use of organic acids as a model to study the impact of gut microflora on nutrition and metabolism. Journal of Applied Poultry Research 11:453-463.

Humphrey, T. and D. Lanning. 1988. The vertical transmission of salmonellas and formic acid treatment of chicken feed: a possible strategy for control. Epidemiology and Infection 100:43-49.

Van Immerseel, F., J. B. Russell, M.D. Flythe, I. Gantois, L. Timbermont, F. Pasmans and R. Ducatelle. 2006. The use of organic acids to combat Salmonella in poultry: a mechanistic explanation of the efficacy. Avian pathology 35:182-188.

Russell J.B. and F. Diez Gonzalez. 1998. The effects of fermentation acids on bacterial growth. Advances in Microbial Physiol 39:205-234.

Kum S., U. Eren, A. Onol and M. Sandikci. 2010. Effects of dietary organic acid supplementation on the intestinal mucosa in broilers. Revue de MédecineVétérinaire 161:463-468.

Rodríguez-Lecompte J.C., A. Yitbarek, J. Brady, S. Sharif, M.D. Cavanagh, G. Crow, W. Guenter, J.D. House and G. Camelo-Jaimes. 2012. The effect of microbial-nutrient interaction on the immune system of young chicks after early probiotic and organic acid administration. Journal of Animal Science 90:2246-2254.

Leeson S., H. Namkung, M. Antongiovanni and E.H. Lee. 2005. Effect of butyric acidon the performance and carcass yield of broiler chickens. Poultry Science 84:1418-1422.

Panda A.K., S.V. Rama Rao, M.V.L.N. Raju and G.S. Shyam. 2009. Effect of butyric acidon performance, gastrointestinal tract health and carcass characteristicsin broiler chickens. Asian-Australasian Journal of Animal Sciences 22:1026-1031.

Fischer, E.N and H.L. Classen. 2000. Age and enzyme related changes in bacterial fermentation in the ileum and caecum of wheat-fed broiler chickens. In Proceedings, Twenty First World's Poultry Congress, Montreal and Canada August:20-24.

Bedford, M.A. and H. Schulze. 1998. Exogenous enzymes for pigs and poultry. Nutrition research reviews 11:91-114.

Parsippany, N.J. 2008. Non-starch polysaccharide enzymes for poultry.Proceedings of the 6th MIDatlantic nutrition confrence, University of Maryland.

Bedford, M.R. 2009. The use of NSPases for improving efficiency of nutrient extraction from corn for poultry. Poultry Bulletin 11:91-114.

Cowieson, A.J., M.R. Bedford and V. Ravindran. 2010. Interactions between xylanase and glucanase in maize-soy-based diets for broilers. British Poultry Science 51:246-257.

Kamal, A.M. and N.M. Ragaa. 2014. Effect of dietary supplementation of organic acids on performance and serum biochemistry of broiler chicken. Nature and Science 12:38-45.

Ma, J., J. Wang, S. Mahfuz, S. Long, D. Wu, J. Gao and X. Piao. 2021. Supplementation of mixed organic acids improves growth performance, meat quality, gut morphology and volatile fatty acids of broiler chicken.Animals 11:3020.

Ebeid, T., I. Al-Homidan, M. Fathi,R. Al-Jamaan, M. Mostafa, O. Abou-Emera and A. Alkhalaf. 2021. Impact of probiotics and/or organic acids supplementation on growth performance, microbiota, antioxidative status, and immune response of broilers. Italian Journal of Animal Science 20: 2263-2273.

Vahjen, W., A. Mader, F. Knorr, I. Ruhnke, I. Röhe, A. Hafeez and J. Zentek. 2014. The effects of different thermal treatments and organic acid levels in feed on microbial composition and activity in gastrointestinal tract of broilers. Poultry Science 93:1440-1452.

Ficagna, C.A., G.M. Galli, E. Zatti, B.M. Sponchiado, B.G.D.O. Cecere, G.L. Deolindo and A.S. daSilva. 2022. Butyric acid glycerides in the diet of broilers to replace conventional growth promoters: effects on performance, metabolism, and intestinal health. Archives of animal nutrition 76:191-204.

Abdelrazek, H.M.A., S.M.M. Abuzead, S.A. Ali, H.M.A. El-Genaidy and S.A. Abdel-Hafez. 2016. Effect of citric and acetic acid water acidification on broiler's performance with respect to thyroid hormones levels. Advances in Animal and Veterinary Sciences 4:271-278.

Akaichi, A., A. Jebali, O. Abbes, S.H. Taieb, M. Feki, K. Kaboudi and N. Boudhrioua. 2022. Effect of humic acid and organic acids, alone or in combination, on blood biochemical constituents and humoral immune response in broiler chickens. Livestock Science 258:104880.

Reda, F.M., I.E. Ismail, A.I. Attia, A.M. Fikry, E. Khalifa and M. Alagawany. 2021. Use of fumaric acid as a feed additive in quail's nutrition: its effect on growth rate, carcass, nutrient digestibility, digestive enzymes, blood metabolites, and intestinal microbiota. Poultry Science 100:101493.

Qiu, K., W. He, H. Zhang, J. Wang, G. Qi, N. Guo and S. Wu. 2022. Bio-fermented malic acid facilitates the production of high-quality chicken via enhancing muscle antioxidant capacity of broilers. Antioxidants 11:2309.

Sumanu, V.O., C. Byaruhanga, A.M. Bosman, S.O. Ochai, V. Naidoo, M.C. Oosthuizen and J.P. Chamunorwa. 2023. Effects of probiotic (Saccharomyces cerevisiae) and ascorbic acid on oxidative gene damage biomarker, heat shock protein 70 and interleukin 10 in broiler chickens exposed to heat stress. Animal Gene 28:200150.

Hajati, H. 2018. Application of organic acids in poultry nutrition. International Journal of Avian and Wild Life Biology 3:324-329.

Creswell, D.C. 1994. Upgrading the nutritional value of grains with the use of enzymes. Technical bulletin, American Soybean Association 341:11-03.

Morgan, A.J. and M.R. Bedford. 1995. Advances in the development and application of feed enzymes. Australian Poultry Science Symposium 7:109-115.

Adams, E.A. and R. Pough. 1993. Non-starch polysaccharides and their digestion in poultry. Feed Compounder 13:19-21.

Annison, G. 1993. The role of wheat non-starch polysaccharides in broiler nutrition. Australian Journal of Agricultural Research 44:405-422.

Dunn, N. 1996. Combating the pentosans in cereals. World Poultry 12:24-25.

Hasselman, K. and P. Aman. 1986. The effect of ßglucanase on the utilization of starch and nitrogen by broiler chicks fed on barley of low or high viscosity. Animal Feed Science and Technology 15: 83-93.

Tiwari, U.P., S.A. Fleming, M.S.A. Rasheed, R. Jha and R.N. Dilger. 2020. The role of oligosaccharides and polysaccharides of xylan and mannan in gut health of monogastric animals. Journal of nutritional science 9: e21.

Bhardwaj, N., B. Kumar and P. Verma. 2019. A detailed overview of xylanases: an emerging biomolecule for current and future prospective. Bioresources and Bioprocessing 6:1-36.

Valente Junior, D.T., J.L. Genova, S.W. Kim, A. Saraiva and G.C. Rocha. 2024. Carbohydrases and phytase in poultry and pig nutrition: a review beyond the nutrients and energy matrix. Animals 14:226.

Mccleary, B. V. Mat and N.K. heson. 1987. Enzymic analysis of polysaccharide structure. Advances in carbohydrate chemistry and biochemistry 44:147-276.

Dhawan, S. and J. Kaur. 2007. Microbial mannanases: an overview of production and applications. Critical reviews in biotechnology 27:197-216.

Balasubramanian, B., S.L. Ingale, J.H. Park, P.C. Rathi, S. Shanmugam and I.H. Kim. 2018. Inclusion of dietary β-mannanase improves performance and ileal digestibility and reduces ileal digesta viscosity of broilers fed corn-soybean meal based diet. Poultry science 97:3097-3101.

Lee, J.T., C.A. Bailey and A.L. Cartwright. 2003. β-Mannanase ameliorates viscosity-associated depression of growth in broiler chickens fed guar germ and hull fractions. Poultry science 82:1925-1931.

Kiarie, E.G., S. Steelman and M. Martinez. 2022. Does supplementing β-mannanase modulate the feed-induced immune response and gastrointestinal ecology in poultry and pigs? An appraisal. Frontiers in Animal Science 3:875095.

Clarke, L.C., T. Sweeney, E. Curley,V. Gath, S.K. Duffy, S. Vigors and J.V. O'Doherty. 2018. Effect of β-glucanase and β-xylanase enzyme supplemented barley diets on nutrient digestibility, growth performance and expression of intestinal nutrient transporter genes in finisher pigs. Animal Feed Science and Technology 238:98-110.

Duarte, M. E., C. Sparks and S.W. Kim. 2021. Modulation of jejunal mucosa-associated microbiota in relation to intestinal health and nutrient digestibility in pigs by supplementation of β-glucanase to corn–soybean meal-based diets with xylanase. Journal of Animal Science 99:skab190.

Tsai, T., C.R. Dove, P.M. Cline, A. Owusu-Asiedu, M.C. Walsh and M. Azain. 2017. The effect of adding xylanase or β-glucanase to diets with corn distillers dried grains with solubles (CDDGS) on growth performance and nutrient digestibility in nursery pigs. Livestock science 197:46-52.

Munyaka, P.M., N.K. Nandha, E. Kiarie, C.M. Nyachoti and E. Khafipour. 2016. Impact of combined β-glucanase and xylanase enzymes on growth performance, nutrients utilization and gut microbiota in broiler chickens fed corn or wheat-based diets. Poultry Science 95:528-540.

Cowieson, A.J., S.L. Vieira and C. Stefanello. 2019. Exogenous microbial amylase in the diets of poultry: what do we know?. Journal of Applied Poultry Research 28:556-565.

Kumar, S. and S. Chakravarty. 2018. The importance of carbohydrates and amylase in human nutrition. Enzymes in Human and Animal Nutrition: Principles and Perspectives; Academic Press: Cambridge, MA, USA.163.

Giuberti, G., A. Gallo, F. Masoero, L.F. Ferraretto, P.C. Hoffman and R.D. Shaver. 2014. Factors affecting starch utilization in large animal food production system: A review. Starch-Stärke 66:72-90.

Saraiva, A., J.L. Donzele, R.F.M.D. Oliveira, M.L.T.D. Abreu, F.C.D.O. Silva and D. Haese. 2009. Available phosphorus levels in diets for swine with high genetic potential for meat deposition from 30 to 60 kg. Revista Brasileira de Zootecnia 38:1279-1285.

Singh, M. and A.D. Krikorian. 1982. Inhibition of trypsin activity in vitro by phytate. Journal of Agricultural and Food Chemistry 30:799-800.

Lei, X.G. and J.M. Porres. 2003. Phytase enzymology, applications, and biotechnology. Biotechnology letters 25:1787-1794.

Partridge, G. and C. Wyatt. 1995. More flexibility with new generation of enzymes. World Poultry 11:17-21.

Van der Klis, J.D., C. Schelle and C. Kwakernaak. 1995. Wheat characteristics related to its feeding value and to the response of enzymes. Proceedings 10th European Symposium on Poultry Nutrition, Antalya, Turkey. World's Poultry Science Association pp.160-168.

Dida, M.F. 2016. Review paper on enzyme supplementation in poultry ration. International Journal of Bioorganic Chemistry 1:1-7.

Williams, P.E.V. 1995. Animal production on feed enzyme to commercial wheat and barley based poultry feeds. 1995. In: California Nutrition Conference, Davis, EUA. Proceedings. University of California pp:203-211.

Schoulten, N.A., A.S. Teixeira and P.B. Rodrigues. 2003. Desempenho de frangos de corte alimentados com racao contendo farelo de arroz e enzimas. Cienc.Agricultural technology 6:1380-1387.

Vieira and L. Sergio. 2003.Oportunidade para o uso de enzimas em dietas vegetarianas. IV Simposio Brasil Sul de Avicultura, Chapeco - SC.Anais.Chapeco pp:91-95.

Rutherfurd, S.M., T.K. Chung and P.J. Moughan. 2002.The effect of microbial phytase on ileal phosphorus and amino acid digestibility in the broiler chicken.British poultry science 44:598-606.

Bach Knudsen, K.E., N.P. Nørskov, A.K. Bolvig, M.S. Hedemann and H.N. Laerke. 2017. Dietary fibers and associated phytochemicals in cereals. Molecular nutrition and food research 61:1600518.

Duarte, M.E., C. Sparks and S.W. Kim. 2021. Modulation of jejunal mucosa-associated microbiota in relation to intestinal health and nutrient digestibility in pigs by supplementation of β-glucanase to corn–soybean meal-based diets with xylanase. Journal of Animal Science 99:skab190.

Freese, E., C.W. Sheu and E. Galliers. 1973. Function of Lipophilic Acids as Antimicrobial Food Additives Nature 241:321-325.

Booth, I. and M. Stratford. 2003. Acidulants and Low pH. In Food Preservatives, 25-47. Boston, MA: Springer US.

Cherrington, C., M. Hinton, G. Mead and I. Chopra. 1991. Organic Acids: Chemistry, Antibacterial Activity and Practical Applications. Advances in Microbial Physiology 32:87-108.

Abdel-Fatt, S.A., M.H. El-Sanhour, N.M. El-Mednay and F. Abdel-Azee. 2008. Thyroid activity, some blood constituents, organs morphology and performance of broiler chicks fed supplemental organic acids. International Journal of Poultry Science 7:215-222.

AM, A.E.H., E.R. Kamel, M.E. Abo-Salem and S.T. Atallah. 2017. Comparative study on the effect of organic acids, prebiotics and enzymes supplementation on broiler chicks' economic and productive efficiency. Benha Journal of Applied Sciences 2:1-8.

Nelson T.W. 1976. The hydrolysis of phytate phosphorus by chicks and laying hens. Poultry science 55:2262-2264

Cromwell G. L. 1992. The biological availability of phosphorus for pigs. Pig News Info, 13:75-78

Brenes A., A. Viveros ,I. Arija ,C. Centeno ,M. Pizzaro and C. Bravo. 2003. The effect of citric acid and microbial phytase on mineral utilization in broiler chicks. Animal Feed Science and Technology 110:201-219

Jongbloed A.W, Z. Mroz, R. van der Weij-Jongbloed and P.A. Kemme. 2000. The effects of microbial phytase, organic acids and their interactions in diets for growing pigs. Livestock Production Science 67:113-122.

Lückstädt C. and S. Mellor. 2011. The use of organic acids in animal nutrition, with special focus on dietary potassium diformate under European and Austral-Asian conditions. In Recent Advances in Animal Nutrition – Australia 18:123-130.

Tacon, A.G., M. Metian and A.A. McNevin. 2022. Future feeds: suggested guidelines for sustainable development. Reviews in Fisheries Science & Aquaculture 30:135-142.

Kallam, N.R.K. and V. Sejian. 2021. Gut health and immunity in improving poultry production. Advances in poultry nutrition research.

Lara, L.J. and M.H. Rostagno. 2013. Impact of heat stress on poultry production. Animals 3:356-369.

Huis, A.V., J.V. Itterbeeck, H. Klunder, E. Mertens, A. Halloran, G. Muir and P. Vantomme. 2013. Edible insects: future prospects for food and feed security.

Dibner, J.J. and J.D. Richards. 2005. Antibiotic growth promoters in agriculture: history and mode of action. Poultry science 84:634-643.

Gaggìa, F., P. Mattarelli and B. Biavati. 2010. Probiotics and prebiotics in animal feeding for safe food production. International journal of food microbiology 141:S15-S28.

Ochieng, P.E., M.L. Scippo, D.C. Kemboi, S. Croubels, S. Okoth, E.K. Kang'ethe and G. Antonissen. 2021. Mycotoxins in poultry feed and feed ingredients from Sub-Saharan Africa and their impact on the production of broiler and layer chickens: a review. Toxins 13:633.

Thirumalaisamy, G., J. Muralidharan, S. Senthilkumar, R. Hema Sayee and M. Priyadharsini. 2016. Cost-effective feeding of poultry. International Journal of Science, Environment and Technology 5:3997-4005.

Mottet, A. and G. Tempio. 2017. Global poultry production: current state and future outlook and challenges. World's poultry science journal 73:245-256.

Yahav, S. 2009. Alleviating heat stress in domestic fowl: different strategies. World's Poultry Science Journal 65:719-732.

Shang, Y., S. Kumar, B. Oakley and W.K. Kim. 2018. Chicken gut microbiota: importance and detection technology. Frontiers in veterinary science 5:254.

Knudsen, K.E.B. 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Animal feed science and technology 67:319-338.

Bedford, M.A. and H. Schulze. 1998. Exogenous enzymes for pigs and poultry. Nutrition research reviews 11:91-114.

Izat, A.L., N.M. Tidwell, R.A. Thomas, M.A. Reiber, M.H. Adams, M. Colberg and P.W. Waldroup. 1990. Effects of a buffered propionic acid in diets on the performance of broiler chickens and on microflora of the intestine and carcass. Poultry Science 69:818-826.

Cowieson, A.J. and H.V. Masey O'Neill. 2013. Effects of exogenous xylanase on performance, nutrient

digestibility and caecal thermal profiles of broilers given wheat-based diets. British poultry science 54:346-354.

National Research Council (US). Subcommittee on Poultry Nutrition. 1950. Nutrient Requirements of Poultry (No. 1). National Academy of Sciences.

Ricke, S.C., D.K. Dittoe and K.E. Richardson. 2020. Formic acid as an antimicrobial for poultry production: A review. Frontiers in Veterinary Science 7:563.